A 40 MHz Level-1 trigger scouting system for the CMS Phase-2 upgrade

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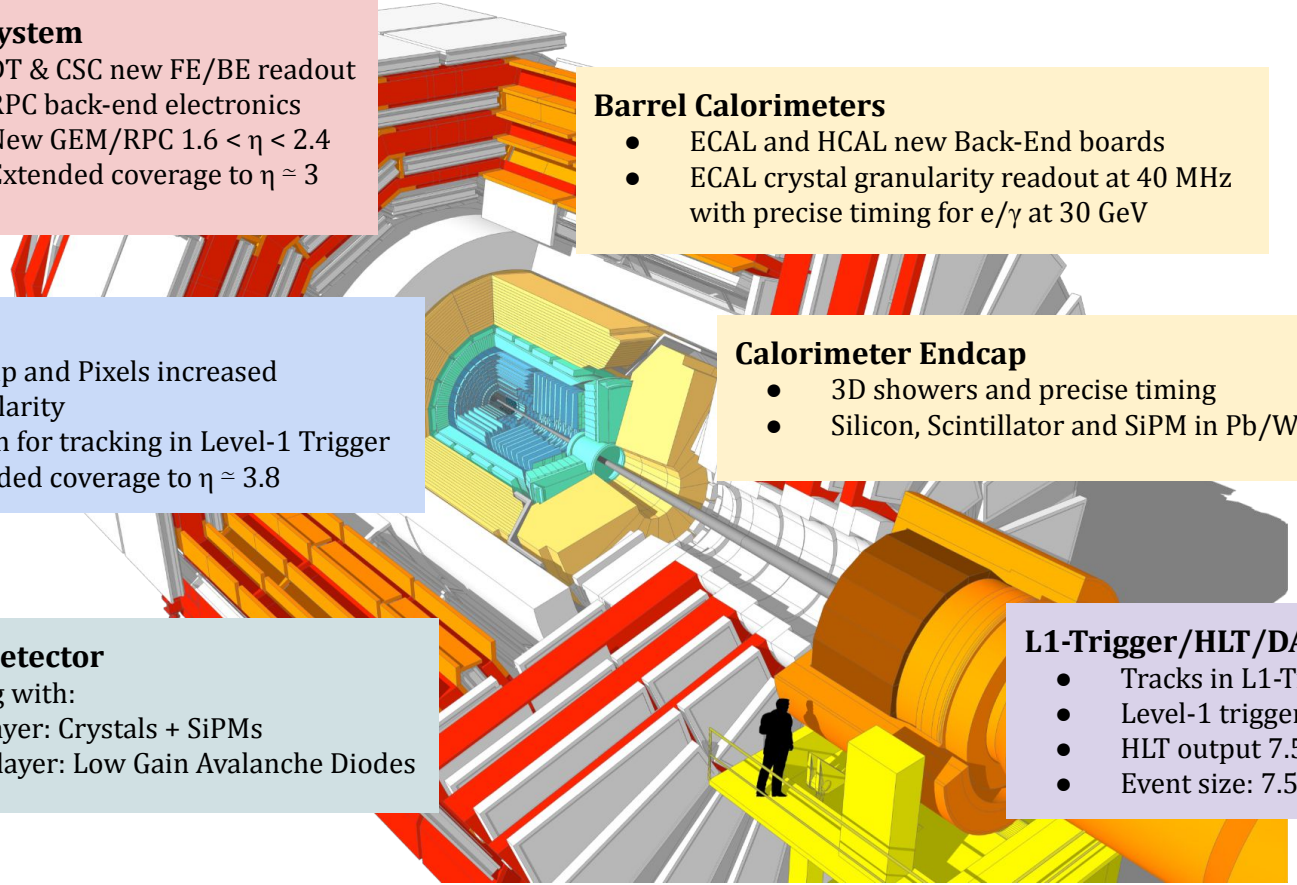
A new CMS for HL-LHC

Muon system
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

Barrel Calorimeters
- ECAL and HCAL new Back-End boards
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV

Tracker
- Si-Strip and Pixels increased granularity
- Design for tracking in Level-1 Trigger
- Extended coverage to $\eta \simeq 3.8$

Calorimeter Endcap
- 3D showers and precise timing
- Silicon, Scintillator and SiPM in Pb/W-SS



MIP Timing Detector

Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

L1-Trigger/HLT/DAQ
- Tracks in L1-Trigger at 40 MHz
- Level-1 trigger output 750 kHz
- HLT output 7.5 kHz
- Event size: 7.5 MB

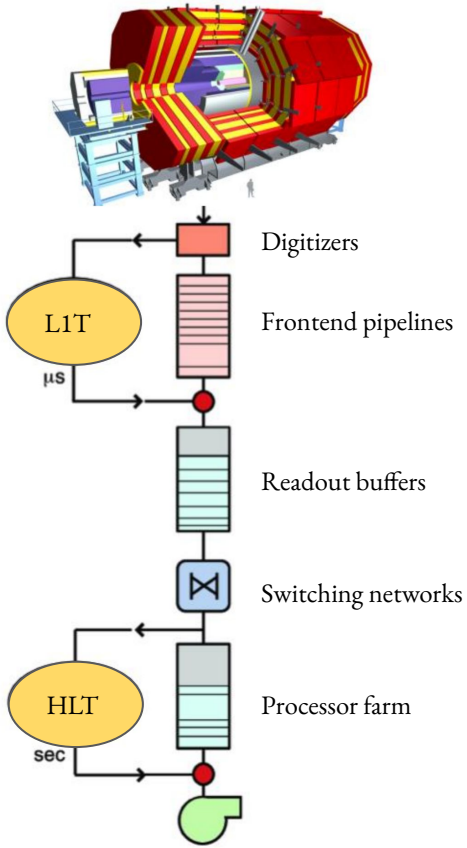
CMS triggers in two stages

Phase-[0&1], 2008-2025

Peak pile up (up to): **60**
40 MHz bunch crossing rate

100 kHz Level-1 trigger accept rate

2 kHz high-level trigger output rate



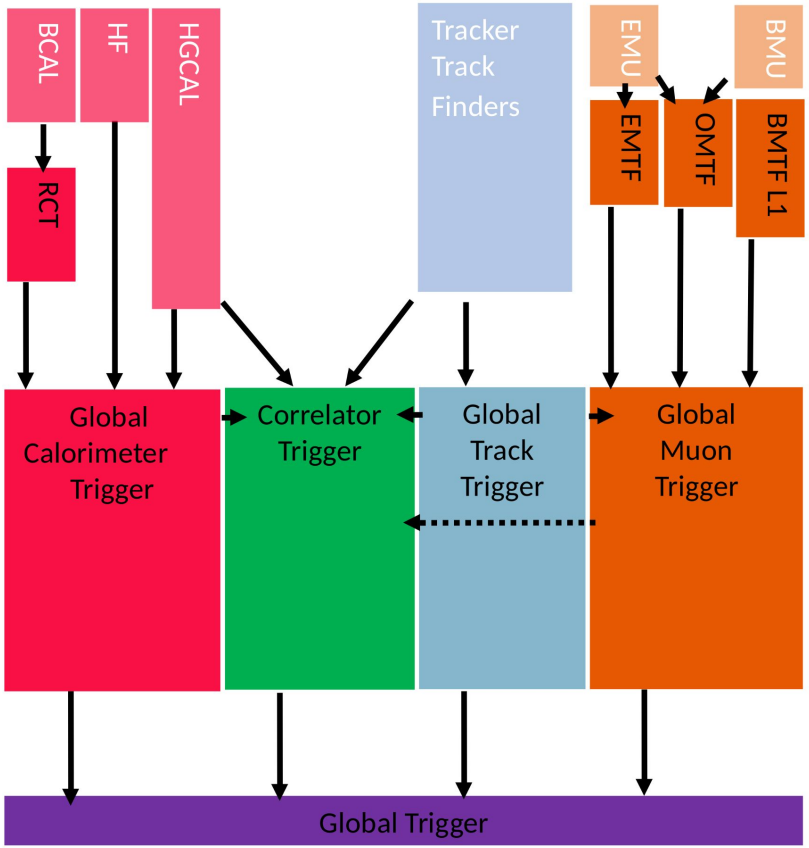
Phase-2, 2029-

Peak pile up: **200**
40 MHz bunch crossing rate

750 kHz Level-1 trigger accept rate

7.5 kHz high-level trigger output rate

A Level-1 trigger for 200 pile-up



- 12 μs latency
  - Increased from less than 4 μs
- Advanced object reconstruction in firmware
  - Tracker tracks
  - Vertex finding
  - Displaced muons
  - High precision calorimetry
  - Particle flow
- Evolution of current Global Trigger algorithms
  - Topological trigger algorithms at higher resolution
    - Including invariant/transverse mass cuts
  - Inter-BX algorithms (up to ±3 bunch crossings)
- Machine learning algorithms
  - For reconstruction, particle ID, and in Global Trigger

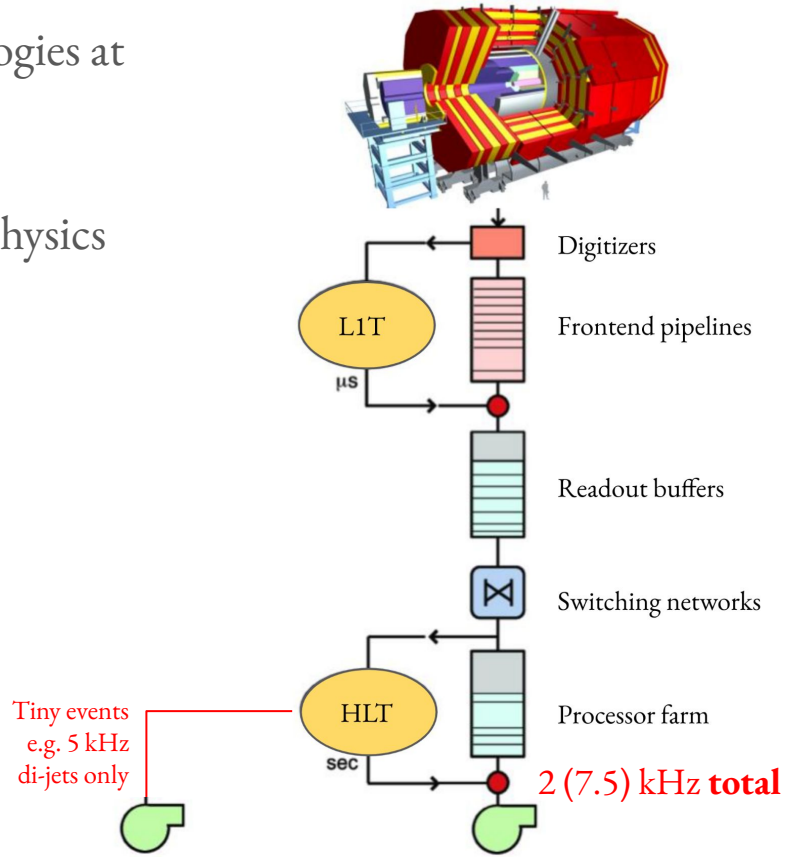
Data scouting in a nutshell

Analyze partial events (only subset of detectors or limited resolution) at much higher rate than possible for full events.

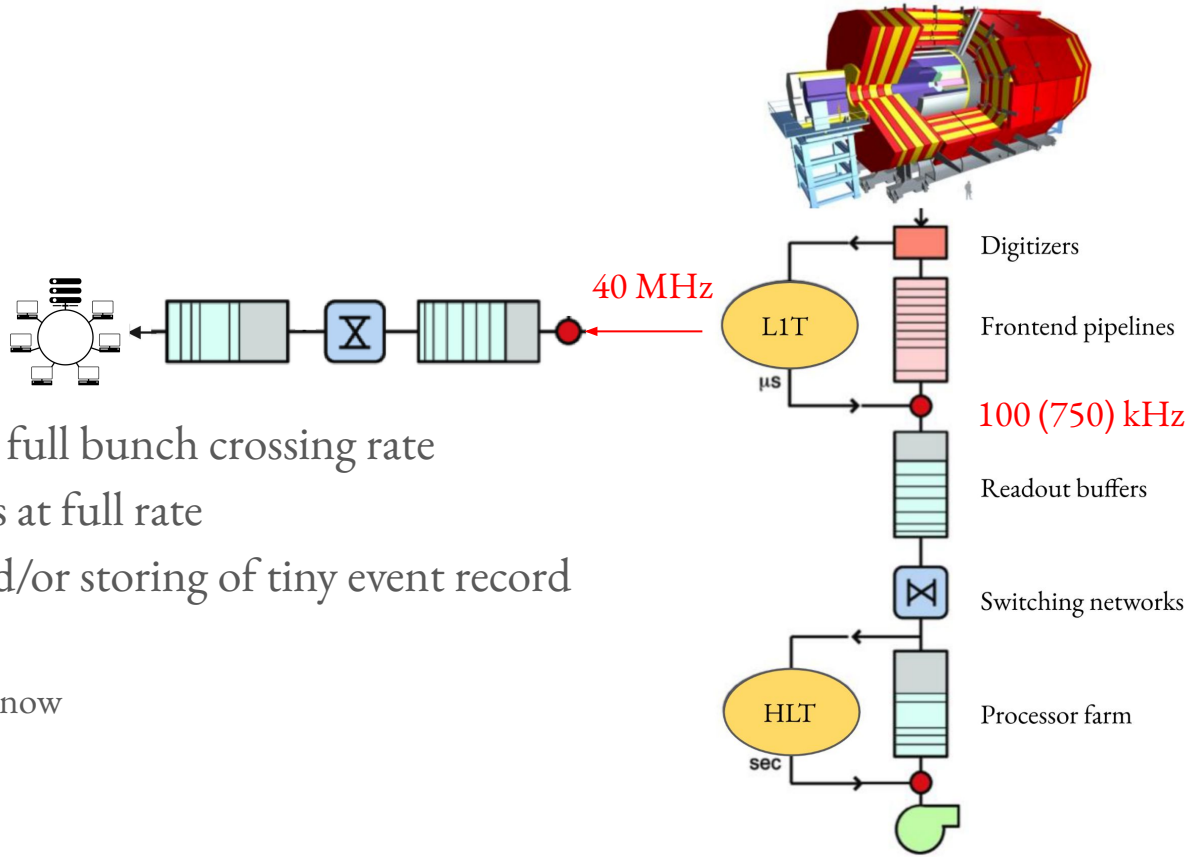
Enables study of exotic signatures that cannot be fit into the trigger budget.

HLT scouting

- Save HLT reconstructed objects for certain topologies at higher rate than would fit into HLT bandwidth
  - Process needs to fit into L1 budget
- Successfully used in CMS since 2011 for several physics analyses
  - Low-mass di-jets https://doi.org/10.1007/JHEP08(2018)130
  - Di-jet resonances in three-jet events https://doi.org/10.1016/j.physletb.2020.135448
  - Di-muons https://doi.org/10.48550/arXiv.1912.04776



Level-1 data scouting



- Acquire L1 trigger data at full bunch crossing rate
- Analyze certain topologies at full rate
- Semi real-time analysis and/or storing of tiny event record
- Planned for Phase-2
  - Demonstrator taking data now

Doing physics at the bunch crossing rate

Scouting may be useful if search for rare process that is

- Difficult to select at Level-1 trigger
  - Available algorithms give low efficiency at attributed rate budget
- Possible to study with resolution available at Level-1 trigger
  - Alternative: Scouting for new signal → then point Level-1 trigger to it

Several Physics channels identified where Level-1 scouting could make a difference:

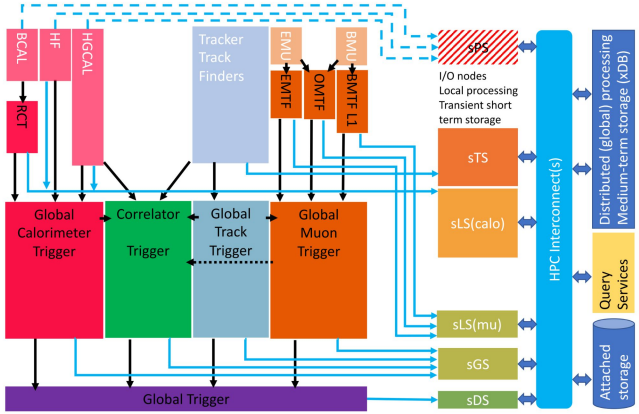
Dark photon, flavour anomalies, classic B physics (e.g., $B \to \tau\tau$), $W \to 3\pi$, ...

Monitoring at the bunch crossing rate

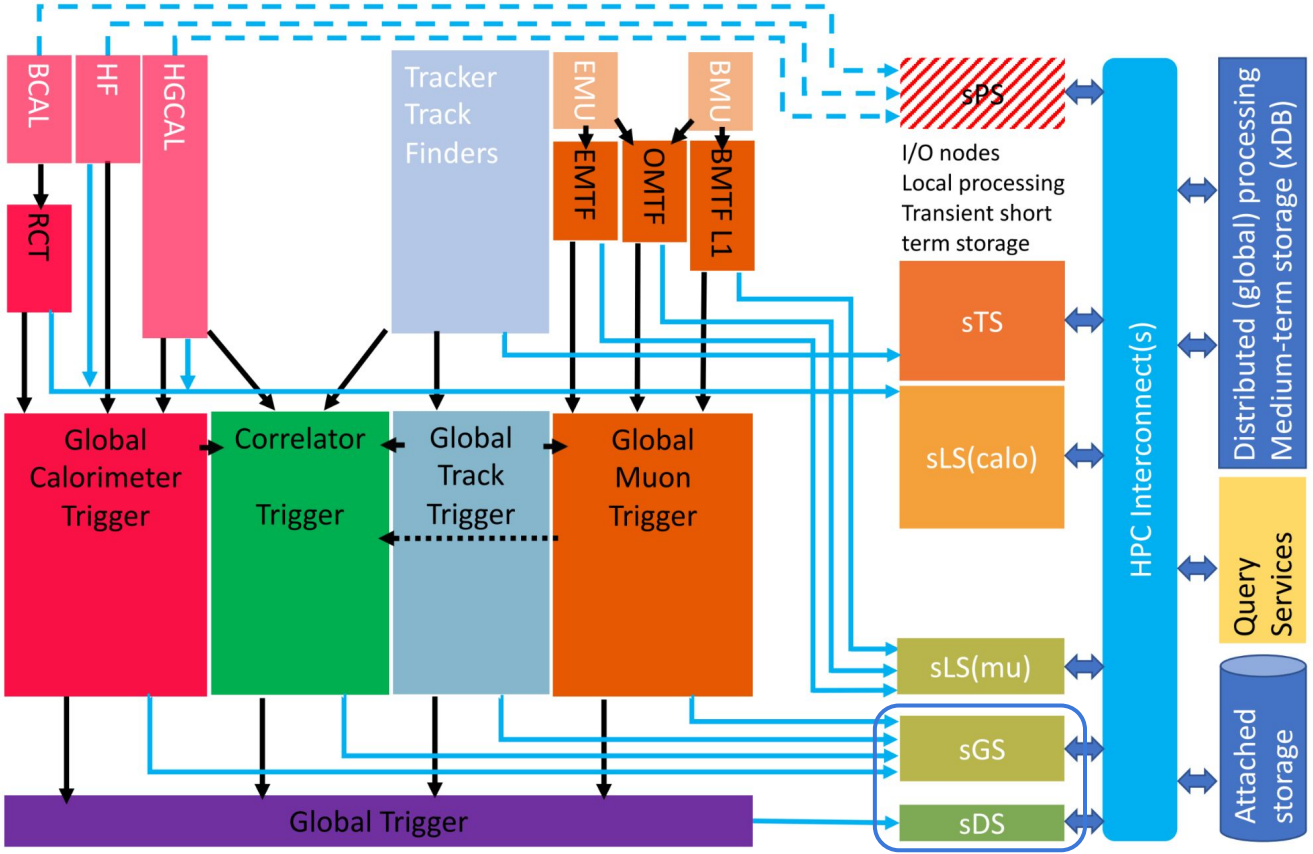
- High statistics "super data quality monitoring" possible with the scouting system
  - Study pre- and post-firing without special trigger configurations
  - Real-time heatmaps to quickly spot problematic channels
  - High statistics data-emulator cross-checks possible
    - Run the trigger emulation on the input objects and compare to outputs
  - Unaffected by issues in the readout system
    - e.g., if detector is blocked due to excessively high rate from a trigger object
- Per-bunch luminosity measurements
  - Using muons, physics channels with high statistics, etc.

Ingredients

- Trigger data captured from **spare outputs of L1T boards**
  - Same **25 Gbps serial optical links** and protocol used for the Level-1 interconnects
- **FPGA boards** receive trigger data
  - Zero-suppression, local pre-processing (e.g. re-calibration using ML) in FPGA
  - Data transmission **to I/O nodes via TCP/IP**
- I/O nodes
  - **CPU, GPU, other accelerators**
  - Use distributed algorithms to extract features while data are buffered in the short-term memory
  - Interesting features and/or full "events" (multi-bx possible) streamed over interconnect to processing farm
- Distributed global stream processing and storage into "feature DB"
  - Organizes features in "searchable" data structures for medium term storage
- Analysis by query, **analysis results to permanent storage**



L1 Data scouting: An analysis facility at 40 MHz



Stageable architecture

- Baseline proposal to receive Global Trigger inputs

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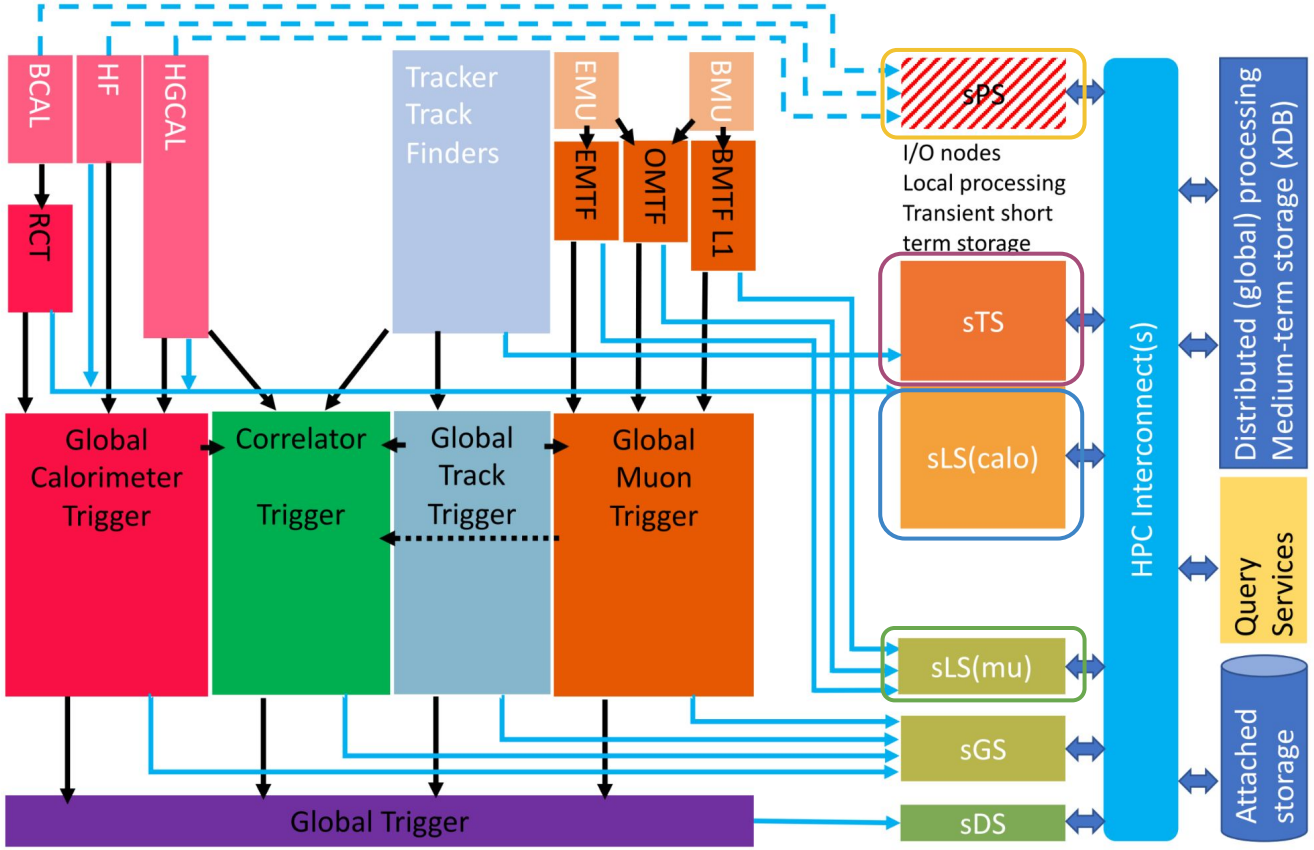
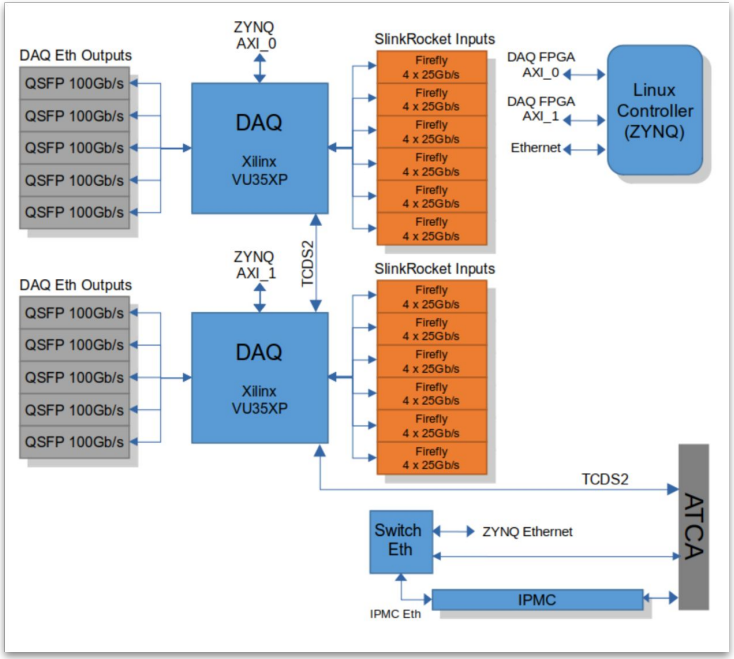


Stageable architecture

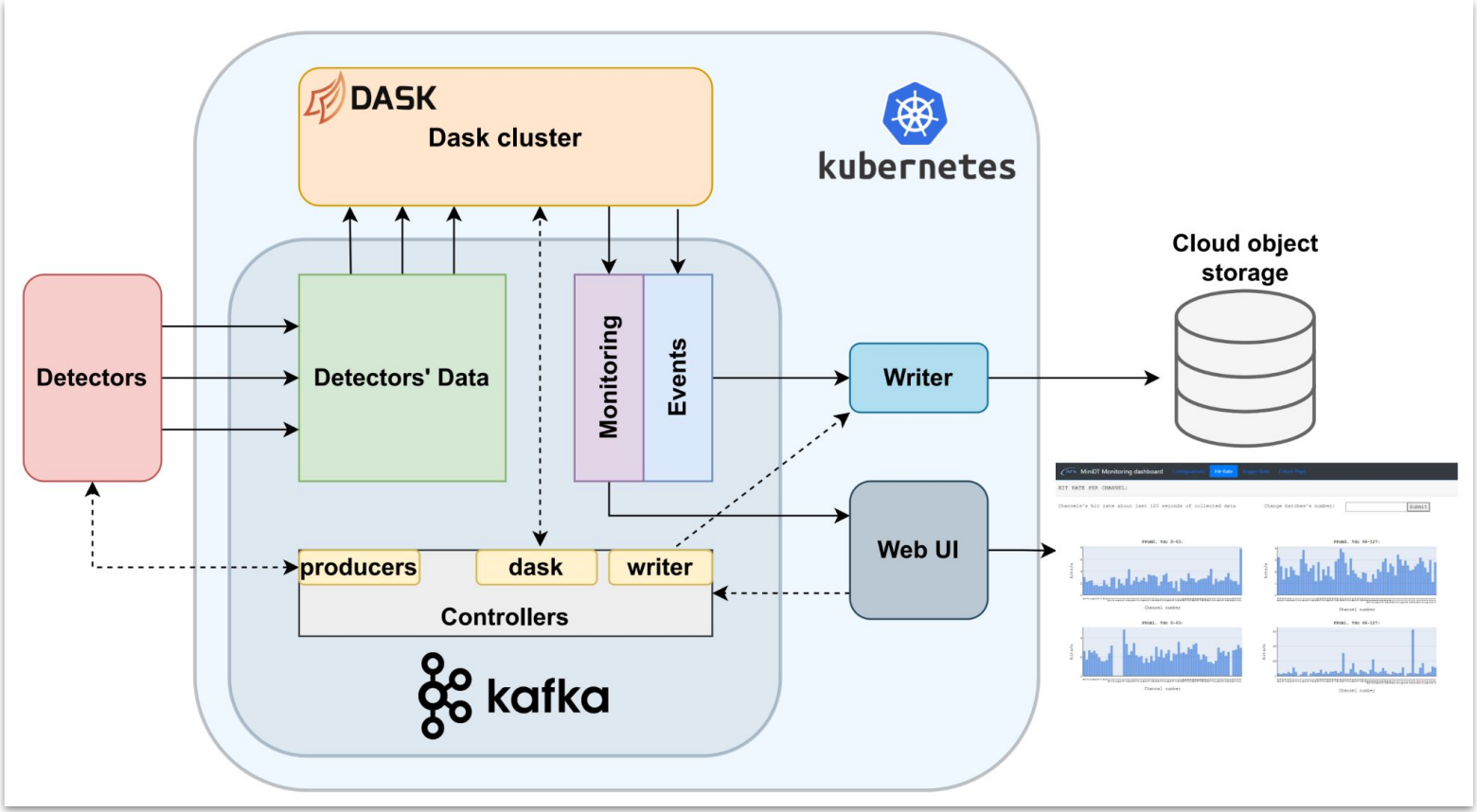
- Baseline proposal to receive Global Trigger inputs
- Can later be expanded in multiple stages
  - Local reconstruction
    - Muons
    - Calorimeters
  - Tracker tracks
  - Calorimeter primitives

The Phase-2 scouting readout board

- Using DAQ800 hardware platform
  - Currently being designed as CMS Phase-2 readout board
  - **Two powerful Xilinx VU35P** FPGAs
  - 6x4 FireFly inputs per FPGA
    - **48x 25 Gbps total input**
  - 5 QSFP outputs per FPGA
    - **10x 100 Gbps total output**
- Firmware
  - Will be able to profit of developments for detector readout
    - TCP/IP sender near-identical to DAQ800
      - **Demonstrated already in the Phase-1 upgrade**
  - Receiver and pre-processing modules scouting-specific
    - Will require moderate zero suppression



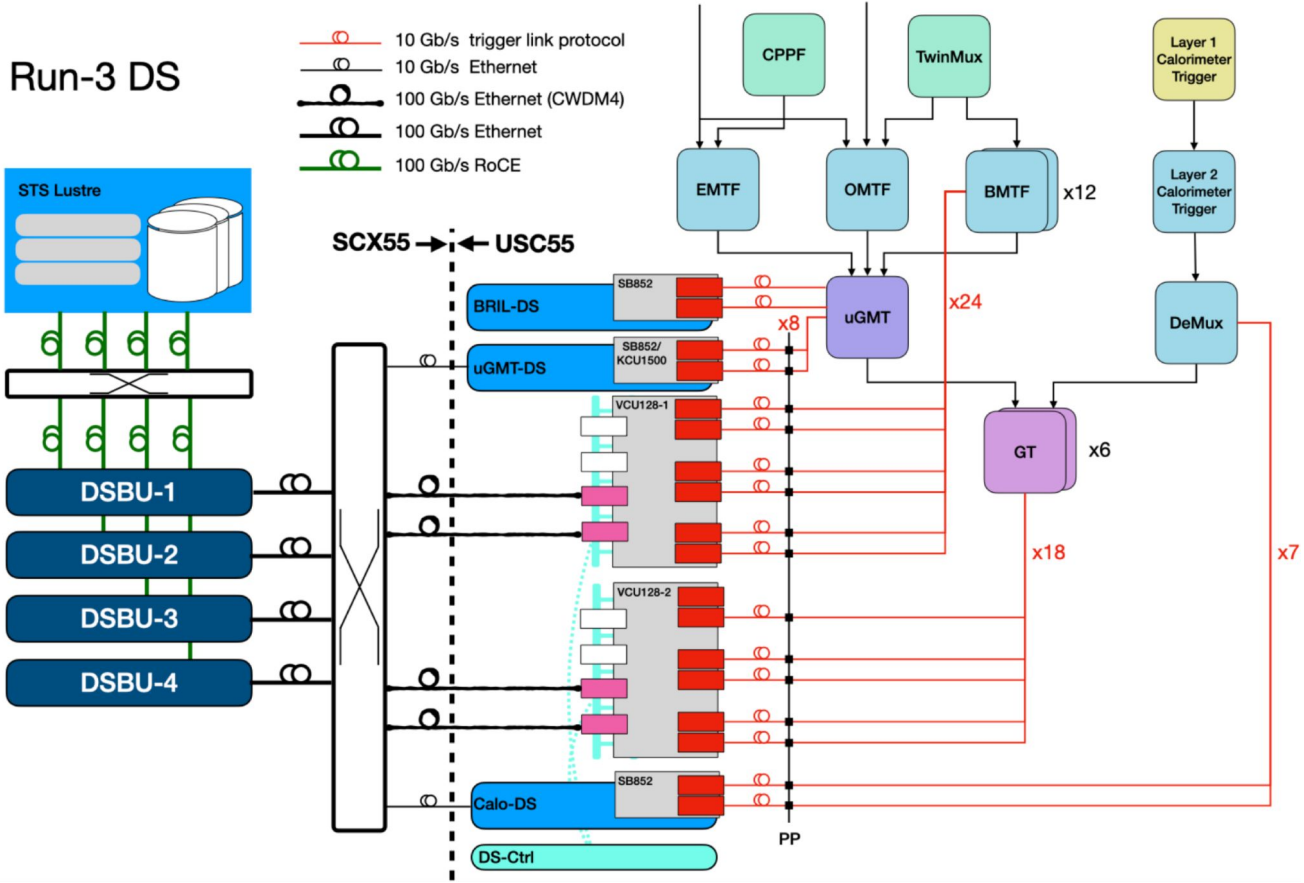
Distributed computing at the LHC bunch crossing rate



From https://doi.org/10.48550/arXiv.2111.05155

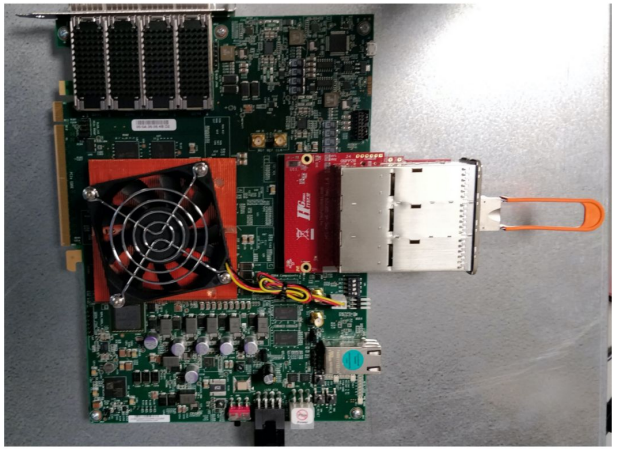
A scouting demonstrator for Run-3

Run-3 demonstrator architecture

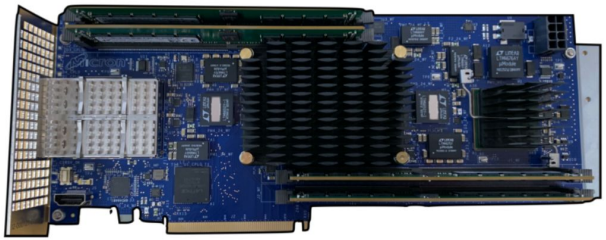


Ingredients

- Xilinx VCU128
  - Approximately the connectivity of ½ DAQ800 board
    - 4 on-board QSFP
    - 6 x 4 QSFP FMC mezzanine
  - Based on **VU37P FPGA**
  - Data transfer to be performed via TCP/IP
    - Currently demonstrated via direct memory access (DMA)
- Micron SB852
  - Can perform machine learning inference with Micron DLA
  - Data is transferred by DMA to host computer



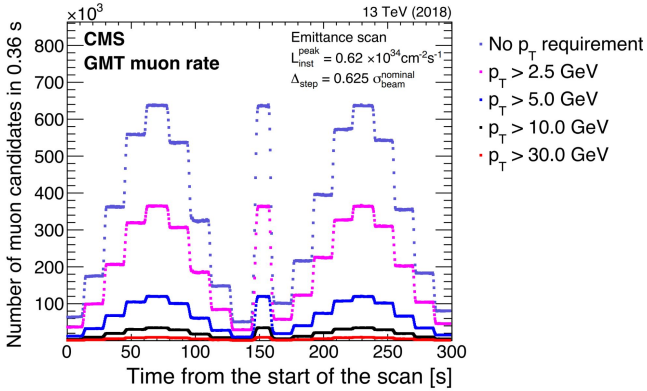
VCU128

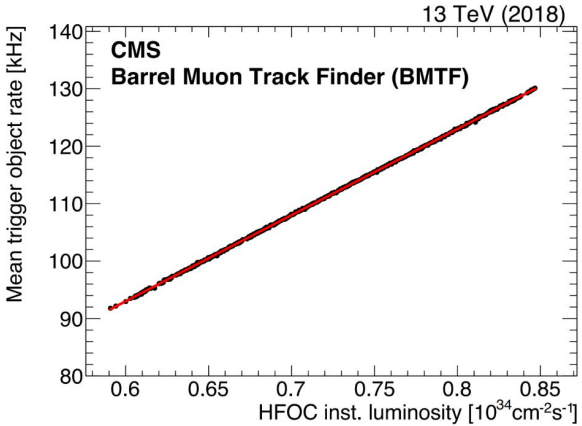


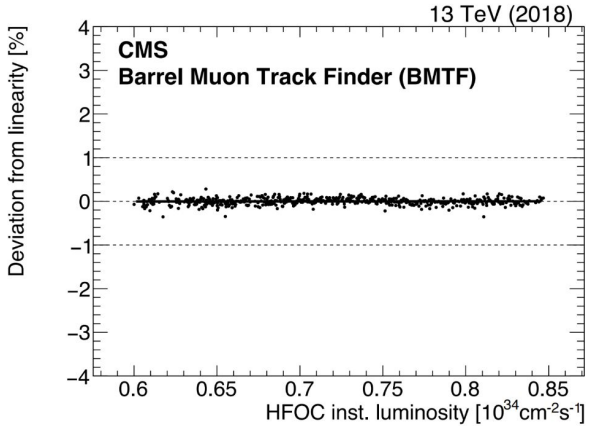
SB852

Measuring luminosity with all muons

- Data taken during emittance scan in 2018
  - Beams moved in x (or y) w.r.t. each other at the beginning and end of each LHC fill
  - Method to find beam overlap
- uGMT output muons sent to scouting system
  - Number of muons seen proportional to luminosity
  - Results consistent with luminosity measured by other luminometers

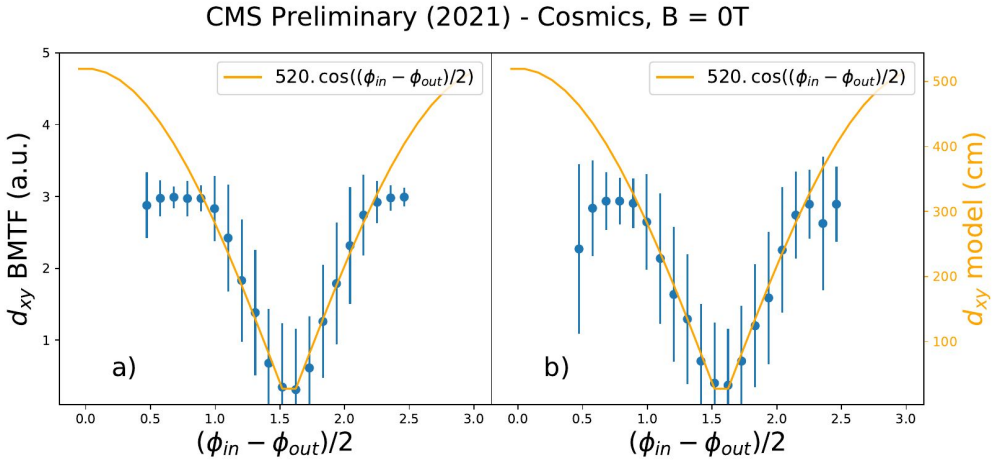


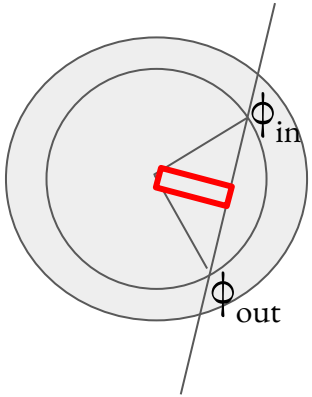




Shown in CMS Phase-2 BRIL TDR.

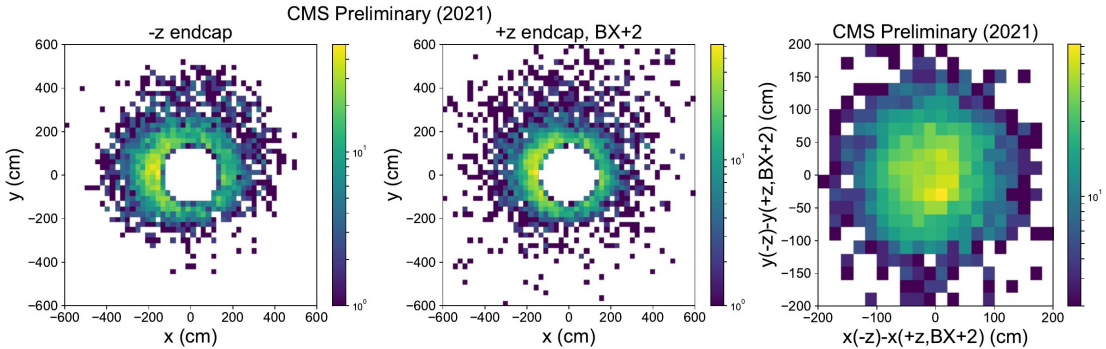
Studying muon trigger impact parameter assignment

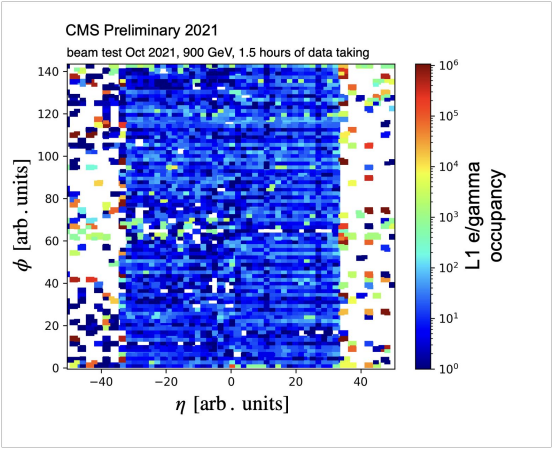




- Considering incoming and outgoing cosmic muon legs as pairs
  - **Idea:** $d_{\text{Muon detector}} * \cos([\phi_{in} - \phi_{out}]/2) \sim d_{xy}$
    - $d_{\text{Muon detector}} \sim 5.2$ metres
- Require muon trigger data from two subsequent bunch crossings
  - Not always feasible due to limited readout bandwidth

First Run-3 data with beams





- Recorded beam halo in endcaps during the October 2021 LHC beam test
  - Muons seen in bunch crossing N in negative endcap appear in positive endcap in bunch crossing N+2

- First data taken from calorimeter trigger
  - Commissioning in progress
  - We see the expected distributions of e/g, tau, and jet objects

Summary

- We will deploy a novel 40 MHz data scouting system for the CMS Phase-2 upgrade in 2029
  - Trigger data streamed at the bunch crossing rate into IO nodes
    - Identified DAQ800 board to perform trigger readout and propagation to nodes
  - Analysed in realtime or tiny events stored for later analysis
  - Investigating distributed computing technologies for this task
- A demonstrator system has been in operation since end of 2018
  - Initially taking data from the Level-1 Global Muon Trigger
  - From mid-2021 added Level-1 Calorimeter Trigger inputs
  - Planning to significantly extend the system with inputs from Barrel Muon Track Finder and Global Trigger during the course of CMS Run-3
  - Two processing boards are targeted for the final Run-3 system:
    - VCU128, a close cousin of the DAQ800 board foreseen for the Phase-2 system
    - Micron SB852, with machine learning inference capabilities
- First results demonstrating the capabilities of the data scouting system were shown